

Recent outcomes and the state-of-art detection scenarios of black holes

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Abstract. Black holes are a hidden secret in humans' heart. This paper will basically focus on the current status of observing black holes as well as the state-of-art detection schemes. Specifically, we will discuss the classifications, theorems of black holes and also the problems encountered by modern knowledge. According to the analysis, the basic types of black holes and the way of detection of black holes are demonstrated. Meanwhile, shows the theories of black holes used in research and some theories about black holes with quantum and holographic image. Overall, these results shed light on guiding the future researches on black hole.

Keywords: Black holes, classifications, related theories.

1. Introduction

The real appearance of black holes in human history is actually that in 1916 Karl Schwarzschild found a solution to Einstein's field equations for a spherically symmetric and non-rotating electroless system in a vacuum, which is known as Vassi solution. This solution is the prototype of all black holes. Humans also defined black holes for the first time, but they were not called black holes at that time. This black hole solved by Schwarzschild is also called the Schwarzschild black hole. However, in the early stage, scholars have made a lot of foreshadowing for the definition of black holes. At the end of the 17th century, some scholars proposed theoretically objects with escape velocities exceeding the speed of light. In 1910 Hans Reisner, Gunnar Nordstrom and Hermann Weyl defined and solved the singularity respectively [1, 2].

After Schwarzschild, plenty of researchers followed to perfect the concept. In 1918, Hans Reisner and Gunnar Nordstrom obtained the solution of the Einstein-Maxwell field equations for a spherically symmetric and non-rotating charge system. In the same year, Friedrich Kotler solved the non-vacuum Schwarzschild solution of Einstein's field equations. In 1963, Kerr solved the Kerr metric and predicted Kerr black holes. In 1969, Penrose discussed the Roger-Penrose process of Kerr black holes and proposed the cosmic censorship hypothesis. A series of studies, including but not limited to the above, have perfected the concept of black holes. In 1971, Cygnus X-1 was finally identified as a black hole, and was the first black hole discovered in human history.

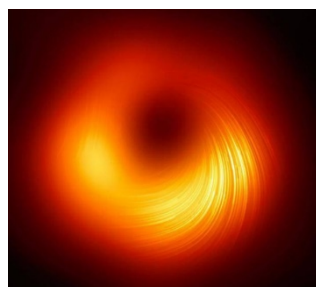


Figure 1 The M87 black hole under polarized light [3].

Human beings have reached a higher level of investigating black holes. As shown in Figure 1, an image of the M87 black hole is appeared under polarized light [3]. To provide a better understanding of later content, being familiar with previous accomplishments is highly recommended. Currently, the image of the M87 black hole was captured by the Event Horizon Telescope. This discovery provides a fabulous opportunity to study the physics behind this black hole (Iván Martí-Vidal). Further investigations of the magnetic field surrounding the black hole and the behaviors of the magnetic field are enabled by results from the EHT research team [4]. A theory was proved to be incorrect from another research from NASA [5]. The previous theory states that black holes would help the formation of stars, while scientists from NASA rejected this idea by pointing out that black holes would be a threat for stars' formation based on their results. The study of a certain group of black holes also assists researchers to learn more about the ultralight bosons, which are a theoretical type of particles with extremely small estimated mass. By calculations toward the black holes under conditions that mass of this type of particles is restricted, scientists from MIT are capable of excluding some ranges of mass predicted on the ultralight bosons.

2. Classification of black holes

Black holes only have three basic quantities, which also correspond to two classification methods, namely mass M charge Q angular momentum L . First of all, black holes are distinguished by mass, which are micro black holes, stellar black holes, intermediate-mass black holes and supermassive black holes.

Micro black holes generally refer to quantum-level black holes. Scientists speculate that quantum-level black holes were formed during the Big Bang. Stellar black holes are the collapse of ordinary massive stars in the universe. When their masses reach the Schwarzschild limit, they will collapse into stellar black holes. It is also the largest black hole in the universe and the one we know best. Once it reaches this level of intermediate-mass black holes, the most massive stars in the universe today cannot naturally form. It is generally formed by stellar black holes slowly accreting other stars, or massive stellar black holes swallowing other black holes. The last supermassive black hole needs a separate description. Supermassive black holes, e.g., quasars at the edge of the universe and the galactic nuclei of some large elliptical galaxies, have yet to have a definite cause for their formation. According to the method of formation of intermediate-mass black holes, the current age of the universe does not have enough time to form such a huge black hole. Not to mention the quasars at the edge of the universe, which are active galactic nuclei created in the early universe and formed not long after the Big Bang. Scientists can only come up with a few conjectures. First, the galactic nucleus of some large elliptical galaxies is composed of many massive stars in the early stage, and the distance between each star is very close, and then these massive stars will quickly decay into black holes. Merged into supermassive black holes due to gravitational effects. In other words, in the early days of the universe, dark matter was very densely packed, and when the mass of these dark matter clusters reached a certain threshold, they would collapse directly into black holes. However, the formation of supermassive black holes has always been a mystery, which still needs to wait for subsequent observations.

In addition to distinguishing black holes by mass, it is to distinguish black holes by their electric charge and angular momentum, and make a Cartesian product of electric charge and angular momentum. This method can divide black holes into four types: Schwarzschild black holes that are not charged and do not rotate, Kerr black holes that are not charged but have angular momentum, R-N black holes that are charged but do not rotate, and Kerr black holes that are both charged and rotating Newmans black hole.

The Schwarzschild black hole is the most classic black hole and the earliest mathematical black hole derived from theory. Schwarzschild black holes are also called static black holes, or ideal black holes. The center of a Schwarzschild black hole is a singularity, and the Schwarzschild radius distance from the singularity is the event horizon of the black hole. The viewport is a hypersurface. The

Schwarzschild equation is:

$$R = \frac{2GM}{c^2} \quad (1)$$

with the metric of:

$$ds^2 = c^2 \left(1 - \frac{2GM}{c^2 r}\right) dt^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 - r^2(d\theta^2 + \sin^2 \theta d\phi^2) \quad (2)$$

where G is the gravitational constant, c is the speed of light, and M is interpreted as the mass of the object generating gravity.

Next is the R-N black hole. The biggest difference between him and the Schwarzschild black hole is that there are two horizons, an inner horizon and an outer horizon. If the charge of the R-N black hole increases, the distance between the two horizons will become smaller and smaller, and eventually they will merge into one, forming an extreme R-N black hole. If the extreme R-N black hole is further charged, the view interface disappears, forming a naked singularity. Naked singularities should not appear in reality in theory, so Roger Penrose, a physicist who won the 2020 Nobel Prize in Physics, proposed a hypothesis in 1969-the cosmic censorship hypothesis. The simple explanation is that when a naked singularity appears, a cosmic law will form a horizon to wrap the naked singularity.

Then, there are Kerr black holes with only angular momentum. A Kerr black hole has no singularity, but an odd ring pulled by huge angular momentum. Since ordinary stars have rotation, stellar black holes are generally Kerr black holes or Kerr Newman black holes. Meanwhile, the Kerr black hole also has two horizons, the difference is that there is a static boundary beyond the external horizon of the Kerr black hole. The limit of rest is the boundary of whether the object is at rest, and within the limit of rest, the object can never reach rest relative to space-time. The reason is that due to the huge angular momentum of the black hole, this part of the region will have a very large drag effect in the region between the static limit and the event horizon. In 1963, Kerr solved the Einstein field equations of an uncharged symmetrical rotating body in a vacuum, and derived the Kerr metric:

$$ds^2 = - \left(1 - \frac{2Mr}{\Sigma}\right) dt^2 - \frac{4aMr \sin^2 \theta}{\Sigma} dt d\phi + \frac{\Sigma}{\Delta} dr^2 \quad (3)$$

where

$$\Delta = r^2 - 2Mr + a^2, \Sigma = r^2 + a^2 \cos^2 \theta \quad (4)$$

Here, M is the mass of the rotating object; a is the rotation parameter or specific angular momentum, which describes the rotation of the object, which is related to the angular momentum J, and the relationship is $a = J/M$; All physical quantities are in geometric units: $c=G=1$.

Finally, there are Kerr Newman black holes, which have both charge and spin. Kerr-Newman black holes have the properties of both Kerr black holes and R-N black holes: there are two horizons and there are no singularities but odd rings.

3. Detection of Black holes

3.1 Detection schemes

Any type of detectable light cannot be emitted by black holes in the universe. However, astronomers are still able to find them and learn much about them. This is done by two traditional methods of detecting black hole.

First way is observing stars around the black holes. For example, in the center of milky way galaxy, there is a black hole. Owing to the large dense and mass of the black hole, this black hole has a large gravitational force, i.e., all stars of galaxy is spinning around the black hole similar to earth is spinning around the solar. Therefore, astronomers are able to know whether there is a black hole in some specific place of universe.

Second way of detecting black hole is by observing the matter falling into the black hole. The existence of black hole jets will accompany with matter falling. The principle of this phenomenon is the gas settles into an accretion disk and become very hot. That is because it is moving fast, and the

gas particles are collide violently with each other. The temperature will be heating up to approximately tens of thousands of degrees, so the accretion disk is going to shine in ultraviolet or X-rays. Observing the X-rays means that a black hole is having a jet there.

However, nowadays, Event Horizon Telescope which is a new method which is different from the previous method have been created. It is consisted of several telescopes around the world, the name of members as shown in table 1. The main target of EHT is observing Sgr A*(black hole in the center of milky way galaxy) and M87*(a supermassive black hole in the center of M87). The difference between EHT and traditional method is that EHT collect the image of event horizon of black hole directly, then astronomers will analyze the image [6, 7].

Table 1. Telescopes which constitute Event horizontal telescope.

Heinrich Hertz Submillimeter Telescope	Caltech Submillimeter Observatory	Sub-Millimeter Array
Atacama Pathfinder Experiment	Institute de radioastronomy millimetrique	Atacama Lare Millimeter Array
Atacama Submillimeter Telescope Experiment	James Clerk Maxwell Telescope	Northern Extended Millimeter Array
Combined Array for Research in Millimeter-wave Astronomy	Large Millimeter Telescope	The South Pole Telescope

3.2 Principle

The EHT project combines data from several very-long-baseline interferometry (VLBI) stations around earth.

3.2.1 VLBI and Data analysis

These telescopes are used at same time by VLBI, then the data in every single one can be combined to one image. The angular resolution is depended on λ/B , lambda is observation of wavelength and B is projection distance between antennas. As this ratio decreases, the angular resolution will increase. Due to the large data, data transmission is impossible for using internet, therefore, using Solid state disk (SSDs) is necessary. However, normal SSDs are not suit for all observation station. For example, the Large Millimeter Telescope in the top of Sierra Negra, some of SSD is broken because of the low pressure and temperature. To solving this problem, scientists using Helium-Filled Hard Drives (HDDs) instead. Helium creates less drag and turbulence when HDD platters spin. It is able to use at cooler temperatures, and when sealed, it keeps out humidity. The efficiency and reliability of disks is most important of implementation of EHT. The reason of that is the data produced by telescopes in one second is in terms of gigabits. During five days, approximately 500TB data will be collected by one telescope, Whole of EHT will collect 7PB data, they can fill 1000 to 2000 HDDs.

After this step, data is analyzed by a supercomputer which has 800 correlators consisting of CPU connected by a 40 Gbit/s network [6]. By using a special software, data will be converted to a single image, it is also called “silicon lens” which are lens that using data instead of light. The resolution of this image is equal to an image took by a telescope which has a size as earth [7].

3.2.2 Building a model and simulation

Black hole is a simple object, according to No Hair Theorem proposed by John Archibald Wheeler, astronomers can describe characteristic of black hole by only mass, charge and spin [9]. What make black hole complex is the surrounding of black hole. Astrophysicists create a mathematics model and simulation according to general relativity. Einstein has forecasted telescopes will observe a shadow which is nearly circle, it looks like a black circle has a colorful circum. However, if the shape is not circle, it means that general relativity needs to be corrected [10].

3.3 Plan of observation

The Event Horizon Telescope program will carry on only one observation per year. The time is depended on climate and whether both of Sgr A* and M87* in the sky [11]. The climate is an important factor of observation is due to the wavelength which astronomers need to observe is able be absorbed by steam. In addition, most of EHT stations have a stable climate in winter. Therefore, winter is the best season which is chosen to do the observation.

3.4 Detection schemes

If Sgr a* and M87* do not have event horizon, the accretion around them will cause the wavelength of radiation reach to the peak. However, EHT is unable to observe this phenomenon, it demonstrates they should have event horizon. The definition of black hole is having event horizon [11]. Form the models of two black holes, their rotating vectors are significant titled with respect to the direction of observation.

In general relativity, the object around black hole is larger when observing form a long distance. After taking into account the scattering caused by the interstellar medium, the millimeter wave radiation observed by astronomers is still smaller than expected 30%. Because millimeter wave radiation is originated from accretion, it has Doppler effect so that radiation is not asymmetry in different direction.

The bright of emitted radiation from Sgr A* varies with time, but the size of radiation area does not change. The principle of this phenomenon is still not clear, whereas the data of EHT demonstrates this changing take place near the accretion. The radiation from the center of M87 indicates that black hole is rotating quickly. Simultaneously, astronomers speculate that the large jets of M87* is produced by magnetic field. In 2019.4.10, astronomers proposed one image, which is the supermassive black hole in the center of M87*. This is the first direct observation of a black hole.

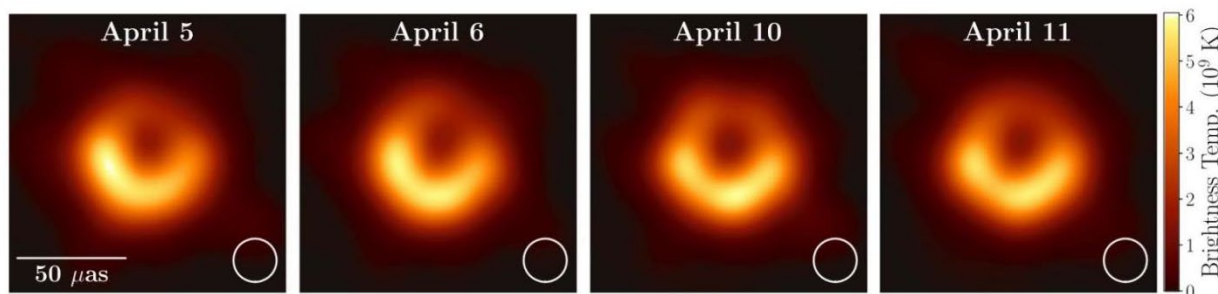


Figure 2 Four nights of data were taken for M87* during the observing window of the EHT, and whilst the diameter of the disk stayed relatively constant the location of bright spots moved, possibly indicating gas that is orbiting the black hole. Credit: EHT Collaboration [11].

4. The state-of-art theorem

4.1 Quantum information

To have a better understanding of the later content, familiarity of the concepts of quantum information is essential. Hence the quantum information should be stated before the further details. This field concentrates more on taking in information from matter at the scale like atoms. To prove or obtain information behind the phenomenon, observation has been considered as a crucial approach to gain data while the measurements and experiments are responsible to quantify the observation. Information is scientifically a physical concept that is already written in the state of a quantum system. The quantum mechanics is exploited to explain the properties of matter at the microscopic level, and the knowledge of quantum information is desired to obtain the wanted information from the properties given in the quantum mechanics. For instance, information of matters that are lost in black holes will be deleted as the Hawking Radiation flows from the Event Horizon, only bringing the data of angular

momentum, charges and total mass out in the particles. There are more details in this field [12], for example the quantum bit, which state could be written as

$$|\Psi\rangle = a|0\rangle + b|1\rangle \tag{5}$$

where a and b are numbers in complex forms, and $|\Psi\rangle$ belongs to the square of C which is the two-dimensional Hilbert Space.

4.2 The Hawking Radiation

Based on the Bekenstein-Hawking Entropy [13], the temperature of a black hole could be derived to be

$$T_{BH} = \frac{hc^3}{16\pi^2 k_B GM} \tag{6}$$

Implying that a black hole is able to radiate energy and therefore to lose mass. Nothing can surpass light, hence how the mass or energy leave the black hole. It shows that the thermal radiation from a black hole is actually a quantum effect [13], which proves that nothing is faster than light from the radiation. Additionally, the cause of this type of radiation was discovered by Hawking, which is the particle-antiparticle pair production at the Event Horizon of the black holes. Another question comes up, which is the origin of the particles or antiparticles. This issue can be solved by an outstanding result from quantum field theory that says empty space is actually not empty. Scientists have named the place that the particles and antiparticles are formed as vacuum fluctuations. For another fact is that these particles commonly annihilate with each other during a small period of time due to the uncertainty principle, which can be expressed as:

$$\Delta E \Delta t \sim \frac{h}{4\pi} \tag{7}$$

After knowing the origin of this particles, the correlations of this with the black holes are obviously important. Hawking himself found out that the vacuum fluctuations occur closely to the Event Horizon of black holes. Some probabilities that one of the particles could escape after its first appearance from the Event Horizon of the black holes are deduced by Hawking, where the probabilities depend on the temperature of the black holes [13]. The remained particle then would drop into the black holes, then there is no chance for the annihilation between the two particles to happen. During this process, the black holes are gradually losing energy and mass from the Event Horizon.

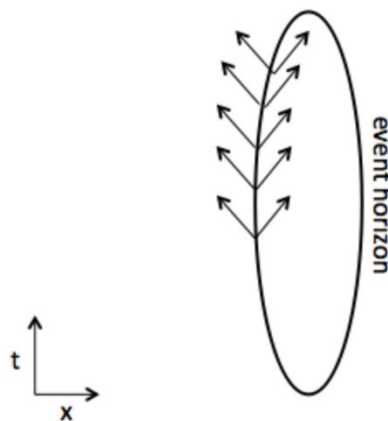


Figure 3 The process of a black hole loses one of the particle from a particle-antiparticle pair over time.

Fig. 3 clearly illustrates the process of which the black holes lose mass and energy. The arrows on the graph refers to the particles and antiparticles generated at the Event Horizon, where one escapes and one falls back into the black holes. This process will continue over time until the total mass of the black holes has evaporated.

To relate this with quantum information, finding that a pair of particle and antiparticles that has consequences in one Hawking emission could be expressed as

$$|\Psi_{HR}\rangle = \frac{|1, 1\rangle + |0, 0\rangle}{\sqrt{2}} \quad (8)$$

The $|1\rangle$ refers to the existence of the particles, while $|0\rangle$ means the absence of the particles. The letters A or B have the meanings that A bit is outside the Event Horizon and B bit is inside the Event Horizon. The two bits are entangled with each other because an outsider or observer has already known that there is an antiparticle inside the black holes if the observer measures the related particle outside the black holes. In spite of the $a(T)$ and $b(T)$ are depicting that this process is crucially to be thermal, scientist still can express it with the Hawking Radiation as:

$$a(T)|1\rangle_A|1\rangle_B + b(T)|0\rangle_A|0\rangle_B \quad (9)$$

Here the expression for the state of Hawking emissions is obtained, by analyzing this expression more information could be derived combined with more previous knowledge.

5. Limitations and Future prospects

Contemporarily, there are some unsolved problems about black hole until now. A traditional example is black hole information paradox. In quantum physics, information will be preserved forever. Hawking radiation demonstrates that the loss of particles will decrease the volume of the black hole. These particles will bring the information out of the black hole. Nevertheless, if this theory is true, general relativity will be destroyed. The reason for this is in general relativity, there are several states of black hole, in the process of changing state, the original information is going to be destroyed. In the final state, the black hole will become a point which has ignored volume and infinity density so that there are no items can escape form it. So far, the principle of this paradox remains unclear

In the future of black hole research, black hole information paradox should be a main research orientation, this theory is relating to whether there are objects can escape the gravitational force of black hole. In the meantime, there are two results after scientists understanding this. One of them is general relativity or quantum theorem is wrong. Another is there are some special characteristics of black hole have not been found and both of these two theories are unable to describe it. Regardless of which one is true, modern physics will fact to a revolution.

6. Conclusion

In summary, this paper discusses the latest results of black hole research based on previous papers and information about black holes. Black holes have been a fascinating existence in the universe, and human beings have never stopped the curiosity to study the black holes. With great efforts input in this field, researchers have obtained basic ideas on black holes, where a system is built that contains theories, hypothesis and guesses. Breakouts are gradually made throughout the path to the truth of black holes. For instance, the first picture of the M87 black hole, quantum information and the Hawking information. However, there are still some unsolved problems such as the information paradox. Researchers are working on this paradox to find a possible solution, where this issue is potentially an obstacle on the path to construct the theories of basic particles. Regardless of the difficulties and mistakes made in this field, accomplishments are still gradually contributing the research. Hopefully, it would be capable of telling the truth of black holes and utilize their theories to realize humans in the coming future. Overall, these results offer a guideline for future investigations of black holes and self-improvements on existed research approaches.

7. Authors' Contributions

These authors contributed equally.

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